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Al-Li Alloys – The Analysis of Material Behaviour during Industrial Hot Forging

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Abstract

Al-Li alloys are a promising class of aerospace materials that combine light weight with high strength, comparable to those of steels. In the case of critical components, it is well known that providing the required reliability is impossible without tailoring the output microstructure of the material. This, in turn, requires a clear understanding of the logic behind microstructure formation depending on the total processing history (especially temperature and strain-rate history). However, uniaxial isothermal laboratory tests provide very limited information about the material behaviour. Real forging processes, especially involving complex geometries, sometimes develop quite complicated temperature-strain-rate paths that vary across the deformed part. A proper analysis of the microstructural transformations taking place in the material under these conditions is therefore very important. In this paper, the correlation between the loading history and microstructural transformations was analysed for AA2099 alloy using the hot forging of a disk-shaped component at selected forging temperatures and strain rates. The obtained results were compared to industrial processing maps based on uniaxial tests.

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Keywords: AA2099; Hot-forging; Flow Stability; Microstructure

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1. Introduction

AA2099 is a third generation Al-Li alloy developed primarily for aerospace applications. This generation has better density savings, corrosion resistance, fatigue crack growth resistance, and general strength and toughness in comparison to the performance of second generation alloys such as AA 2090 [1]. In addition, they also have a lower intensity of "brass" crystallographic texture. This reduces property anisotropy - one of the chief shortcomings of the second generation Al-Li alloys [2]. However, the risk of delamination fracture remains in all Al-Li alloys. Fig. 1 shows the initial microstructure of a AA2099 sample in the form of extruded rod and an example of delamination cracks obtained during attempts at cold forming this material. From this viewpoint, hot deformation remains the preferred route for the manufacturing of this alloy. It gives the ability to change the direction of grain flow and control the tendency for texture formation. However, the achievement of these aims requires a careful selection of forging conditions. This is hardly possible via blind trial and error methods, rather a deep understanding of both the mechanics of metal flow as well as microstructural behaviour of the material is necessary.

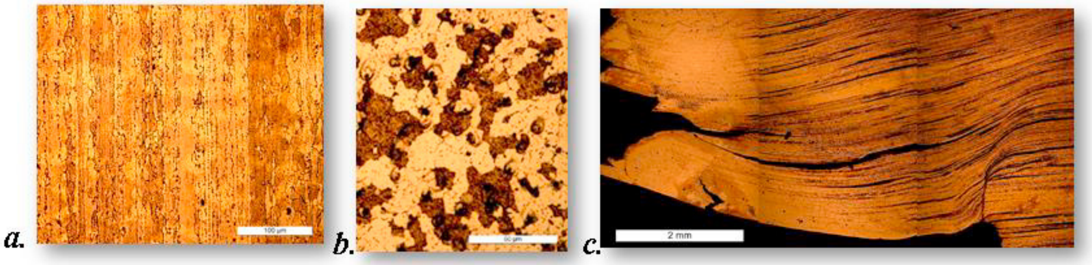

Fig. 1. Initial microstructure of AA2099: a) axial (extrusion) direction, b) transverse direction, c) example of delamination fracture during cold forming.

There are a number of works devoted to metallographic aspects of hot deformation of AA2099, e.g. [3–5] and a few investigations focused on the mechanical behavior of this alloy at elevated temperatures. Zhang *et al.* suggest the use of processing maps (first suggested by Y.V.R.K Prasad [6]) as a basis for the selection of the optimal forging regime. Processing maps consist of a superimposition of the power dissipation efficiency and the instability maps, the first framing the "safe" domain of process parameters and the second enclosing the parameters for avoiding undesirable microstructures [4]. Corresponding processing maps are shown in Fig. 2a for reference, while Fig. 2b shows the metal flow observed during hot forging of a disk geometry (more details in the next section) under different temperatures. It is readily observable that the material demonstrates different levels of flow instability. Based on what may be seen in Fig. 2b, the temperature of 400°C looks to be the best i.e. minimizes the zones of high shear, though this could hardly be deduced from the available processing maps. The aim of this paper is to analyze the specifics of material behavior under the conditions of industrial hot forging and to assess the applicability of the processing maps for process development and optimization.

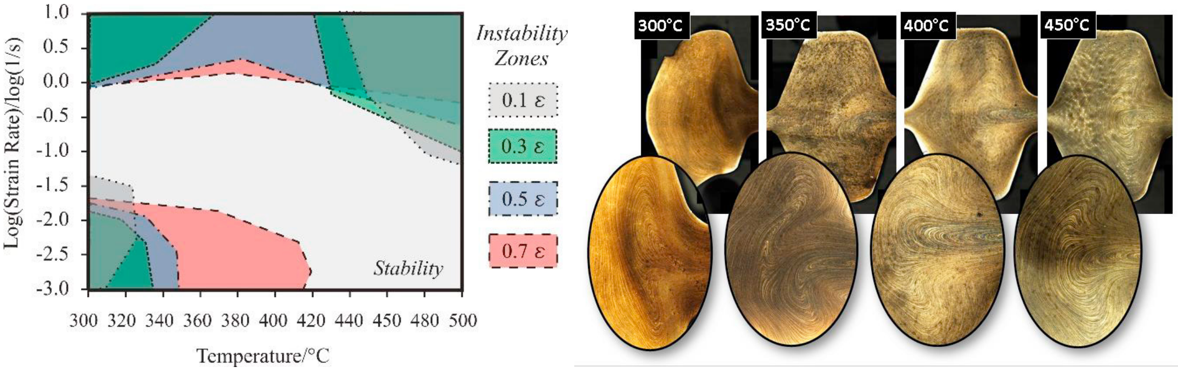

Fig. 2. (a) Processing maps for AA2099 at strains of 0.1, 0.3, 0.5 and 0.7 (summary of data taken from [4]); (b) the etched flow lines in disks forged at different temperatures.

2. Experimental and modelling procedure

The main shortfall of the available experimental data including that used for the construction of the processing maps is the simple nature of the loading involved in the basic material tests. The majority of tests are conducted in either tension or compression at constant temperature and strain rate. These tests are no doubt very important for understanding the role of each process parameter. However, they provide limited information about the behavior of the material under complex loading, typical for industrial processes, see Fig.3. Another limitation of tensile or compression tests is the amount of plastic strain we can achieve (rarely more than 0.7 in true strain); while for hot forging large strains, e.g. between 3-5, are typical. For this reason traditional laboratory tests were complimented in this research with forging trials to investigate more complicated loading.

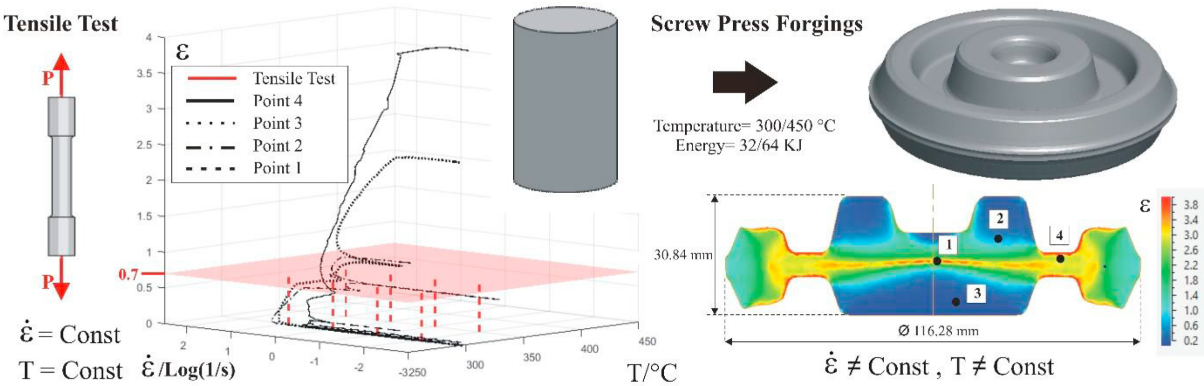

Fig. 3. The difference in thermo-mechanical history of the different points between lab tests and industrial forging.

Forging trials (closed die forging of the disk shape shown in Fig.3) were conducted using a 2100 tonne screw press with forging energies of 64, 56, 40 and 32 kJ for the workpiece pre-heating temperatures of 300, 350, 400 and 450°C, correspondingly. The temperature of the dies was set at 200°C. Forged disks were quenched into water.

Process modelling for the forging trials was performed in the commercial metal forming software, QForm, using a rigid visco-plastic material model calibrated with compression test data. The results of modelling were validated by comparison with the experimental data of the press load profile, shape of the part and the material flow lines. Some results of the last two are shown in Fig.4. Different points of the workpiece were marked within the model and traced through the forging process. Then obtained logs of the sequential values of temperature, equivalent strain rate and accumulated plastic strain were plotted as continuous trajectories in the corresponding 3D space; see Fig.3.

3. Results and Discussion

The validation of the simulation gave good results, which is critical for obtaining trustable thermo-mechanical history at different points. It can be seen (Fig.4) that at the pre-heat temperature of 300°C the dies were under-filled and the outer belt of the disk has quite an asymmetric form. Under-filling happened because the energy of the press (64kJ) in this case was insufficient for completion of forging and the process stopped when the energy of the blow was exhausted. The asymmetry of the metal flow is due to the slightly different temperature and friction conditions between lower and upper die. This effect is not unusual for industrial forging – all parameters of the process are variable within an allowable tolerance window. This was taken into account in modelling to provide matching of the results and obtain robust data for post-processing.

The analysis of instability based on the Dynamic Material Model (DMM) proposed by Prasad *et al.* [6] helped Zhang *et al.* [4] to locate few instability regions by utilizing the principle of the maximum rate of entropy production (shaded areas in Fig. 2). Zhang *et al.* noted that "According to the instability parameter, the processability of 2099 alloy will deteriorate as this alloy deforms at the corresponding process parameters of those [unstable] regions.

Those process parameters should be avoided.” Unfortunately, the recommendations of the authors are impossible to fulfill in the normal forging process. Almost all points of the workpiece during the deformation process “visit” instability regions for shorter or longer periods and this is unavoidable. Correspondingly, one of the first questions of this study was to understand how critical is exposure to such instability regions for the macroscopic material flow, or its microstructural transformations.

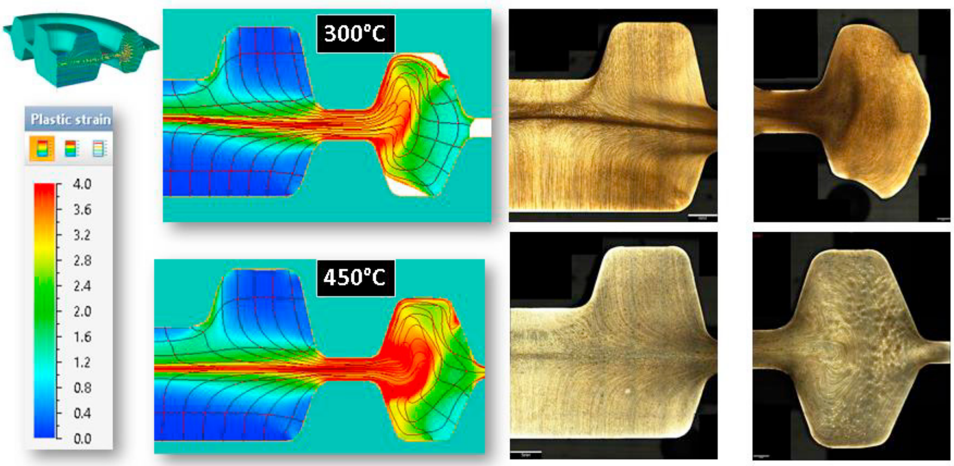

Fig. 4. Validation of the results of process modelling by comparing the obtained results with experimental data (shape of the forged disk and geometry of the flow lines).

As can be seen in Fig. 2, the processing maps and location of the instability regions change with strain. Unfortunately, compression tests used for the construction of these maps are limited to a true strain of circa 0.7, while many of the material points during forging experience much higher strains. To exclude the effect of high strains, only a point with a limited deformation (Fig.5c) was used for the analysis. This point undergoes active deformation only in the beginning of the process, and later maps to the border of the “dead zone” due to localization of the flow in the middle plane of the workpiece. Four trajectories in the space of the thermo-mechanical parameters (i.e. temperature, strain rate and strain) were constructed for the same location in four disks forged at different temperatures (300, 350, 400 and 450°C); Fig. 5 a & b. All these trajectories start and end in the stable zone, but in the middle of the process enter the high stain rate instability zone. In the two lower temperature trials (300 and 350°C) the trajectories also come to the low strain rate instability zone. As per the reports of Zhang *et al.* [4], we can expect adiabatic shear bands and flow localization from the high strain rate instability and additional flow localizations from the low strain rate instability. However, as it can be seen from Fig. 5c, no clear manifestation of these effects are visible in the micrographs. Although there is some difference in the microstructure, and most probably some additional information can be obtained from the EBSD maps, there is nothing, which robustly witnesses about any microstructural instability. The flow appears quite uniform and the initial texture is maintained.

There can be at least two reasons for that. . First, the material examined in the paper [4] did not have a strong initial texture (and it has to be mentioned that anisotropy is not taken into account in processing maps at all). Second, it seems quite logical, that for the development of any effect, the workpiece material has to be exposed to the particular conditions for a certain sufficient amount of “time”. One of the possible ways to treat this problem is to utilize the approach similar to that used in damage accumulation models. For the each fraction of the strain gained within an instability zone some penalty points can be given. After exceeding a certain critical value of these accumulated penalty points, significant instabilities should be observed at the micro and macro level.

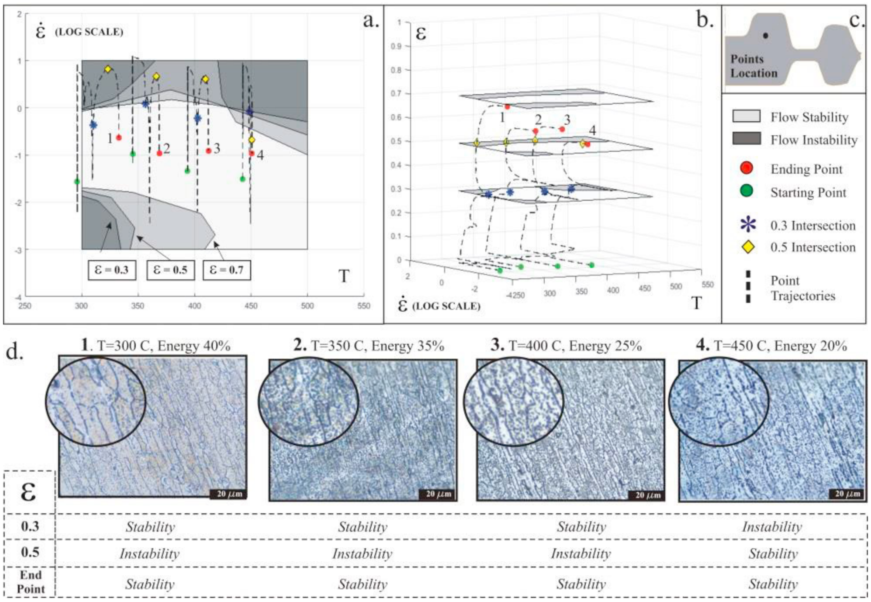

Fig. 5. Trajectories of the thermo-mechanical states of the points with respect to the stability maps: a) projection of the maps and trajectories onto a 2D strain rate-temperature plane; b) 3D view of the same trajectories – with consideration of strain; c) location of the tracked points (same in all four disks); and d) the resulting microstructure in the tracked points in the disks forged at 300, 400, 350 and 400°C.

This unfortunately leads us to one inconvenient question – how do we define the notion of instability at both levels - microstructural and metal flow? Although many of the listed papers are devoted to flow instability, which is a macroscopic effect [3-6], no one of them provides the definition of this phenomenon. The answer to this question is nontrivial. There were fundamental attempts to develop a mathematically robust definition of stability in visco-plastic flow, but this approach is difficult to implement at engineering level of industrial processes [7]. The definition of the stability of the microstructural transformations is hardly easier.

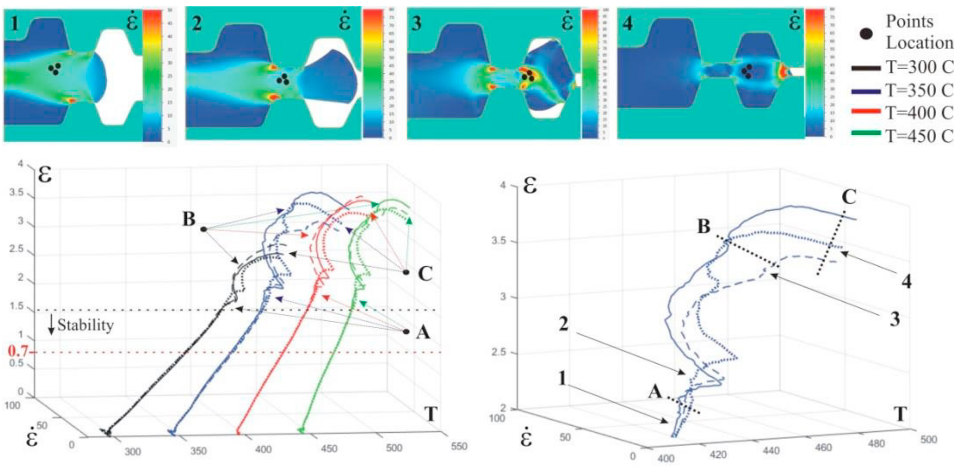

Fig. 6. Reflection of the flow stability via thermo-mechanical trajectories.

At the qualitative (assessment) level, we can try to utilize Lyapunov stability criteria [8]. In its simplified form, it means that a process is stable if a limited variation in the input parameters leads to a limited variation in the outputs. We can try to analyse from this point of view the patterns of the flow lines shown in the beginning of the paper; Fig. 2b. If we select any three geometrically close points (which will all access the zone of unstable flow), these points will play the role of the small variation of the input parameters (i.e. locations of the points). Thermo-mechanical trajectories of the points will be the outputs of the process. If the trajectories of the geometrically close points remain close to each other, the process is stable. The instant when these trajectories begin to deviate from each other will indicate the beginning of stability loss. The bigger the deviation - the more unstable is the flow. This approach is illustrated in Fig. 6. From the beginning to the stage A, the flow is stable. Then from A to B, the trajectories split – flow becomes less stable. Closer to the end (stage C), the flow re-stabilises. The amount of destabilisation is different at different temperatures, which is consistent with the observed patterns of flow lines. It should be noted that flow stability loss starts at about a true strain of 1-1.5 (Fig.6), far above the strains available on process maps. This may be why there was no chance to predict this instability using maps given in [4] (Fig. 2a).

4. Conclusions

The following significant conclusions can be derived based on the above study:

- Processing maps can be useful, but if they are derived based on standard tensile/compression tests, they may have limitations in situations where the (i) temperature and strain rates may be variable, (ii) strains are higher than those achievable using uniaxial lab tests and (iii) strain paths are complex.
- FE modelling can be used to map points within a complex forging to better identify the temperature, strain and strain rate paths. However, there is a certain conundrum involved since the material model in the FE method will have its own limitations, which means that such predictions are likely to have their own uncertainties. This has to be carefully taken into account.
- More meaningful processing maps might be generated using more complex testing scenarios, combining a wider range of laboratory tests (e.g., tension with torsion or other complex loading tests) with industrial trials processes with the help of modelling capabilities.
- In processes with complex thermo-mechanical history, which pass through different stable and unstable zones, “visiting” unstable regions does not immediately lead to material deterioration.
- Accounting for favorable and unfavorable conditions during complex thermo-mechanical processes observed in hot forging requires the development of a smarter model.
- Thermo-mechanical trajectories of points in the space of temperature, strain rate and strain can be used as a measurable output in the analysis of instability in material flow.

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